DECLARATION UNDER 37 CFR 1.131

We, Srikanth Krishnamurthy, Tamer ElBatt, and Dennis Connors, hereby declare that **we invented the subject matter of Patent Application No. 10/816,546 at least as early as the date of April 19, 1999, and by acts undertaken wholly in the United States of America, have diligently pursued this invention until at least the benefit of priority filing date of November 7, 2000 and until the continuation filing date of April 1, 2004.** Tamer ElBatt was unavailable at the time of signing this declaration. However, the other two available inventors, Srikanth Krishnamurthy and Dennis Connors, have signed this declaration.

The invention that is the subject of this patent application was captured in an Invention Disclosure, included herewith as Appendix A. Referring to Appendix A, as noted on sheet 2, box 3, we declare that Srikanth Krishnamurthy first completed a written description of the invention by April 20, 1999. The invention disclosure provides support for the subject matter in all of the claims of Patent Application No. 10/816,546.

We hereby declare that all statements made herein of our own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under 18 U.S.C. 1001 and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

Srikanth - V.K.

Srikanth Krishnamurthy September 11, 2008
Date

Dennis Connors September 11, 2008
Date

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____________________ September 11, 2008
Srikanth Krishnamurthy — Date

Tamer ElBatt — September 15, 2008
Tamer ElBatt — Date

____________________ September 11, 2008
Dennis Connors — Date

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______________________ September 11, 2008
Srikanth Krishnamurthy Date

Dennis Connors September 11, 2008
Dennis Connors Date

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CORPORATE PATENTS AND LICENSING
Loc. CO, Bldg. C01, M/S A126

INVENTION DISCLOSURE

THIS INVENTION DISCLOSURE IS MADE PURSUANT TO MY / OUR INVENTION AGREEMENT WITH HUGHES AIRCRAFT COMPANY.

HUGHES

1. TITLE OF INVENTION **SHEET 1 OF** ____

Power Management for Throughput Enhancement in Wireless Ad Hoc Networks

2. INVENTOR(S)

NAME	PAYROLL NO.	SOURCE CODE	LOC	BLDG	MS	PHONE	MANAGER
Srikanth Krishnamurthy	J3292	30-21-40	MA	254	RL96	5887	Son Dao
Tamer ElBatt	VENDOR	30-21-40	MA	254	RL96	5164	Son Dao
Dennis Connors	J3280	30-21-40	MA	254	RL96	5261	Son Dao

This is to acknowledge that the above Invention Disclosure has been received by Corporate Patents and Licensing. The disclosure will be reviewed at the next Evaluation Committee Meeting of your organization and you will be promptly informed of the results. If you have any questions please contact the patent attorney listed on the bottom of this form.

This sheet will be returned to the inventor(s) as a confirmation of receipt by Corporate Patents and Licensing.

LOSS OF RIGHTS THROUGH RELEASE TO THE PUBLIC

The right to apply for and obtain a valid patent may be lost as the result of certain activities, such as (1) disclosing the invention outside of the company without an appropriate confidentiality agreement with the receiving party; (2) using the invention publicly; (3) using the invention privately to build or test items that are to be sold publicly; or (4) putting the invention "on sale" by selling or offering for sale an item or product that embodies or uses the invention, or is made or tested by use of the invention. Submitting a proposal with the intent to use the invention in the performance of a resulting contract puts the invention "on sale".

Please inform me immediately of any of these activities or any plans to undertake any of them.

ASSIGNED ATTORNEY: ____________ PHONE ( ) ____________

1. TITLE OF INVENTION Power Management for Throughput Enhancement in Wireless Ad Hoc Networks **SHEET 2 OF** ____

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Appendix A

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INVENTION DISCLOSURE

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HUGHES

2. INVENTOR(S)

NAME	PAYROLL NO.	SOURCE CODE			LOC	BLDG	MS	PHONE	MANAGER
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Tamer ElBatt	VENDOR	30	21	40	MA	254	RL96	5164	Son Dao
Dennis Connors	J3280	30	21	40	MA	254	RL96	5261	Son Dao

3. PROOF ON CONCEPTION

A. BY WHOM WAS FIRST DESCRIPTION WRITTEN OR DRAWING MADE?	DATE	TIME SPENT	ACCT. CHARGED	LOCATION OF FIRST DESCRIPTION / DRAWING
Srikanth Krishnamurthy	4/20/99	3 months	CD192A7DL	MA, Bldg. 254
B. TO WHOM WAS INVENTION FIRST DISCLOSED?	DATE			
Yongguang Zhang				

4. REDUCTION TO PRACTICE

A. WAS A DEVICE EMBODYING THE INVENTION CONSTRUCTED AND TESTED OR THE PROCESS PRACTICED?	YES ☐ NO ☒	BY WHOM	DATE STARTED	DATE COMPLETED	TIME SPENT
		Inventor			

B. ACCOUNT CHARGED — TIME	ACCOUNT CHARGED — MATERIAL	PRESENT LOCATION OF DEVICE
CD192A7DL		MA, Bldg. 254

C. PRESENT LOCATION OF DOCUMENTS (DATE SIGNED AND WITNESSED), INCLUDING PHOTOS, DRAWINGS, AND DATA SHEETS SHOWING REDUCTION TO PRACTICE — MA, Bldg. 254

NOTE: ALL EVIDENCE OF CONCEPTION (FIRST DRAWING AND FIRST WRITTEN DESCRIPTION) AND EVIDENCE OF REDUCTION TO PRACTICE (DEVICE EMBODYING THE INVENTION AND TEST DATA) MUST BE RETAINED.

5. RELATION TO GOVERNMENT CONTRACT

A. DOES THIS INVENTION RELATED TO WORK PERFORMED UNDER A GOVERNMENT CONTRACT?	YES ☐ NO ☒	CONTRACT NUMBER AND TITLE
B. IS INVENTION BEING USED ON A GOVERNMENT CONTRACT?	YES ☐ NO ☒	CONTRACT NUMBER AND TITLE

6. RELATED DOCUMENTS AND DISCLOSURE (BY YOU OR BY ANOTHER). PLEASE ATTACH COPY.

A. IS THERE A PUBLICATION OR PUBLIC PRESENTATION RELATED TO THE INVENTION?	YES ☐ NO ☒	DATE	IDENTIFY
B. ARE THERE ANY RELATED INVENTION DISCLOSURES OR PATENT APPLICATIONS?	YES ☐ NO ☒	DATE	IDENTIFY PD NO. ETC.
C. ARE THERE ANY PROPOSALS OR REPORTS OR OTHER DOCUMENTS RELATING TO THIS INVENTION	YES ☐ NO ☒	DATE	IDENTIFY
D. HAS THE INVENTION BEEN USED, DISCUSSED, DEMONSTRATED OR OTHERWISE DISCLOSED OUTSIDE THE COMPANY (SUCH AS TO A VENDOR OR CUSTOMER)?	YES ☐ NO ☒	DATE	TO / FOR WHOM (COMPANY / PERSON)

7. SALE

A. HAS PRODUCT EMBODYING INVENTION OR MADE BY INVENTION BEEN PROPOSED, SOLD, OR OFFERED FOR SALE?	YES ☐ NO ☒	ORDER NO.	ORDER DATE	DELIVERY DATE	DATE OFFERED OR PROPOSED
B. IS PRODUCT EMBODYING INVENTION OR MADE BY INVENTION IN A DELIVERABLE ITEM?	YES ☐ NO ☒	DELIVERY DATE			

HUGHES PROPRIETARY

Srikanth. V.K   Tamer ElBatt
SIGNATURE INVENTOR   8/19/99
DATE

Dennis Connors
SIGNATURE INVENTOR   8/19/99
DATE

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8. SUMMARY OF THE INVENTION

SHEET 3 OF ______

A. GIVE A BRIEF DESCRIPTION OF YOUR INVENTION, PARTICULARLY POINTING OUT WHAT IS BELIEVED TO BE NOVEL (THE "HEART" OF WHAT IS NEW).

The proposal is the first to introduce the notion of *power control* within the context of wireless ad hoc networks. More specifically, we investigate the effect of using different transmit powers, in a wireless ad hoc environment, on the *average power consumption*, and *end-to-end network throughput*. It is believed that this approach leads to reducing the system power consumption and hence prolonging the battery life of mobile nodes. On the other hand, it improves the end-to-end network throughput as compared to other ad hoc networks where all the nodes use the same transmit power. This is due to the tradeoff among the following parameters; *interference ranges*, *average number of hops to reach a destination*, *probability of having isolated clusters*, and *average number of transmissions*.

During operation, the system is supposed to go through *periodic* phases of *specifying and maintaining network connectivity* followed by the data transfer phase. In the *Connectivity Specification* phase, each mobile node is expected to decide the optimal, or near optimal, connectivity range that maximizes the end-to-end network throughput for the current network configuration characterized by the topology, mobility patterns, coverage area, and network load. By the end of this phase, each node will have decided the optimal number of neighbors with which it will maintain direct connectivity. During the *Connectivity Maintenance* phase, each node is expected to broadcast a beacon signal at the maximum power level in a separate reliable signaling channel. Each node, then, ranks every other node according to the received power level from that node. Finally, each node identifies its neighbors and modifies its power level so as to establish direct connectivity to only those nodes. This connectivity information is then transmitted in the signaling channel so that all nodes might accordingly update their routing tables. By the end of this phase, the global network connectivity should be known and the routing tables are up to date. Finally, the *Data Transfer* phase involves the generation of data packets (IP or otherwise). Packets are then routed to their destinations according to the proposed *minimum power routing* protocol, which is essentially the classical shortest path routing, and the link costs are based on the transmitted powers. This power based connectivity definitions are expected to provide enhancement of throughput and reduction of average power when used in conjunction with a contention based MAC protocol.

B. EXPLAIN THE PURPOSE AND ADVANTAGES OF YOUR INVENTION. (WHAT WILL THE INVENTION DO BETTER THAN DONE PREVIOUSLY?)

Power based connectivity definition is a new concept in wireless ad hoc networks. It attempts to improve the end-to-end network throughput and the average power consumption. This is due to the fact that as the power gets higher, and the connectivity range increases, each node would reach almost all other nodes in a single hop. However, since higher powers cause a higher interference level, more collisions occur, and hence there will be more transmission attempts. By reducing the transmission power levels at each node such that the node can directly connect to only a small subset of nodes in the network, the interference zones are considerably reduced. However, under this proposition a packet has to be relayed by many intermediate nodes in order to reach the destination. Since there are a large number of transmissions, throughput may again degrade due to the increase in interference. Our protocol attempts to dynamically reach a near-optimal power level such that the network throughput is brought close to the maximum achievable throughput. This also translates to reducing the total power usage to a level close to the minimum. The major advantage of our approach is power saving, since power is a precious resource in the wireless environment. Moreover, this will lead to improving the throughput as well. Typical networks that might benefit from the concept of power based routing are low mobility (typically pedestrians) wireless ad hoc networks that need to be established for soldiers relaying information for situational awareness on the battlefield, rescue and emergency disaster relief operations.

Srikanth . V. K Tamer ElBatt 8/19/99
SIGNATURE INVENTOR DATE

[signature] 8-19-99
SIGNATURE INVENTOR DATE

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HEUNG-NO LEE [signature] 8-19-99
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Yongguang Zhang [signature] 8-19-99
WITNESS NAME (TYPE) SIGNATURE DATE

PATENT DOCKET NO.
LABORATORIES
AUG 19 1999
PD# 990814

HUGHES

8. **SUMMARY OF THE INVENTION** *(Continued)*

C. IDENTIFY THE COMPANY PROGRAM OR PRODUCT LINE TO WHICH THE INVENTION APPLIES, AND THE EXPECTED VALUE TO THE PROGRAM OR PRODUCT LINE. ALSO IDENTIFY POTENTIAL COMMERCIAL APPLICATION OF THIS INVENTION, INCLUDING AUTOMOTIVE APPLICATIONS, IF ANY.

The invention can apply to any future wireless ad hoc networks. The power based routing is applicable to DARPA wireless ad hoc networks; Small Unit Operations (SUO), Joint Tactical Radio Systems (JTRS), or future tactical radio systems. It is also applicable to sensor networks wherein minimizing power can be of paramount importance.

D. IDENTIFY THE PRIOR ART KNOWN TO YOU WHICH IS IMPROVED UPON OR DISPLACED BY YOUR INVENTION, AND STATE IN DETAIL, IF KNOWN, THE DISADVANTAGES OF THE CLOSEST PRIOR ART.

Various routing protocols have been proposed for wireless ad hoc networks in the literature. Those protocols are mainly focused on establishing routes, and maintaining these routes under frequent and unpredictable connectivity changes [2], [3]. The implicit assumption in most of the earlier work is that nodes' transmitted powers are constant. To the best of our knowledge, there is no prior known work that proposes the concept of mobile ad hoc nodes using different transmit powers. It is evident that this approach is restricted to ad hoc networks of relatively low mobility patterns. If the nodes are highly mobile, the power control protocol might fail to cope with the fast and sudden changes due to fading and interference conditions. In [1], Bambos refers to power control as being widely accepted in the context of cellular (both channelized and CDMA) systems and satellite systems. On the other hand, he refers to the limited attention that power control has received in mobile ad hoc networks. This work investigates the benefits, and possibly the tradeoffs, of deploying different transmit powers in the wireless ad hoc environment. We propose a power management scheme which can be used in conjunction with traditional table-driven routing protocols, with possibly minor modifications. The performance measures are taken to be the *end-to-end network throughput* and the *average power consumption.*

Srikanth V.K. Tamer ElBatt — SIGNATURE INVENTOR — 8/19/99 DATE

SIGNATURE INVENTOR — 8-19-99 DATE

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YONGGUANG ZHANG — WITNESS NAME (TYPE) — SIGNATURE — 8-19-99 DATE

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9. **DETAILED DESCRIPTION** **SHEET 5 OF** ______

DESCRIBE YOUR INVENTION IN DETAIL, USING NECESSARY ADDITIONAL SHEETS

A. BE SURE THAT EACH SHEET IS DATED, AND SIGNED BY EACH INVENTOR AND TWO WITNESSES. (HAC FORM 236C-6 CS SHOULD BE USED, IF PRACTICAL).

B. ATTACH COPIES OF DRAWINGS OR DETAILED REPORTS HELPFUL IN UNDERSTANDING HOW YOUR INVENTION WORKS

C. IF YOUR INVENTION HAS BEEN TESTED, BRIEFLY SUMMARIZED THE TEST RESULTS WHICH CONFIRM THE FUNCTIONS AND ADVANTAGES LISTED IN 8 B ABOVE.

Power Management in Wireless Ad Hoc Networks: Introduction

When the power management scheme is implemented each node transmits at a minimum power level such that only a fixed number of neighboring nodes can hear the transmission. For example, a node might transmit with a power such that only its three closest neighbors can hear its transmission. Thus, in Figure 1 below, node A transmits with a power P_1 such that only it's three nearest neighbors i.e., nodes B, C and D can hear it. Similarly, node D would transmit with a different power, say P_2, such that only it's three nearest neighbors i.e., nodes A, C and E can hear it.

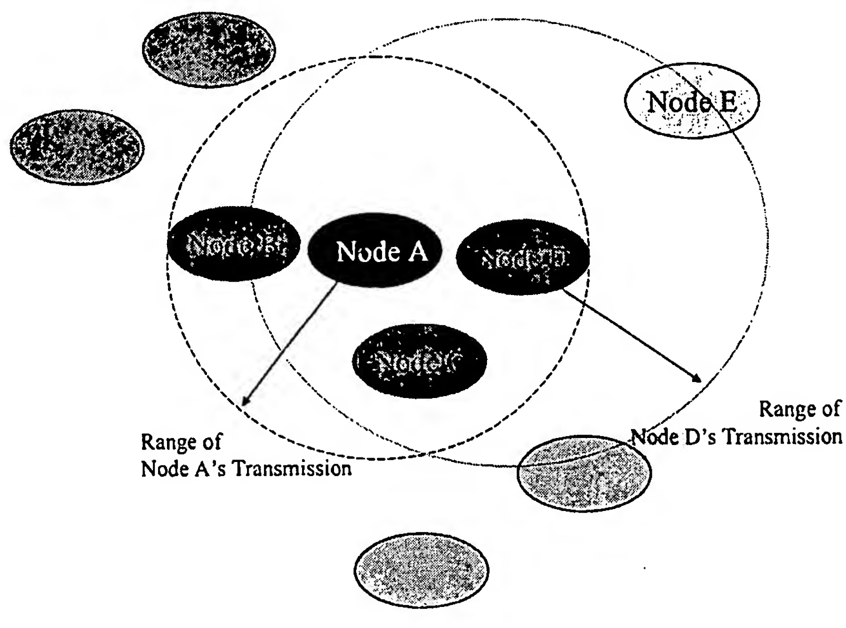

Figure 1: An example of a Power-controlled Ad Hoc Network

Srikanth .V.K Tamer ElBatt 8/19/99

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System Assumptions

1. The wireless ad hoc network consists of *n* nodes; each having a unique ID denoted *Node ID*.
2. The mobile nodes are assumed to have *low mobility* patterns, that is, they are typical *pedestrians*. This, in turn, implies that the network topology changes slowly and the class of *shortest-path routing* protocols is applicable.
3. Each mobile node has direct connectivity to its *N* closest neighbors only, where *N* is to be adapted dynamically in the *Connectivity Specification Phase.*
4. Assume *connectionless (Data-gram)* type of traffic, i.e. routing decisions are to be made on a *packet-by-packet-basis*.
5. The transmit power of any mobile node is upper bounded by a maximum power level denoted as P_{max}. The limited size and weight of the mobile terminal dictate this constraint.
6. The transmit power of any mobile node is lower bounded by the P_{min} constraint. This constraint is essential to avoid partitioning the network into *isolated islands*.
7. Two MAC schemes are deployed in this system in the following two phases:
   - *Connectivity Maintenance Phase:* We assume a contention-free system with a slot, or channel, dedicated to each node. Furthermore, it is assumed that each node transmits a beacon packet at the maximum power level P_{max}. It is worth mentioning that this procedure is to be executed *periodically* every pre-specified number of frames, and when a mobile node moves or fails. Note that any reliable access mechanism may be used instead.
   - *Data Transfer Phase:* We assume a classical *Slotted-Aloha* MAC scheme (Any contention based MAC scheme may be chosen).
8. This protocol assumes the availability of a reliable *reverse channel* that operates on a different frequency band. This channel is essential for performing the following tasks:
   - Sending the *ACK* and *NACK* messages from the receiving node to the transmitting node in order to retransmit packets involved in collisions.
   - If a data packet reaches its destination successfully, the destination node is expected to broadcast a message at maximum power in order to reach the source node. This acknowledgement is needed for each node to compute periodically its end-to-end throughput which is necessary for the operation of the *Connectivity Specification* protocol.
   - Exchanging various nodes' end-to-end throughput computations, in order to find the average end-to-end network throughput.
9. Guard bands are crucial in order to keep the nodes in the network time-synchronized. More specifically, the slot duration is assumed to be larger than packet duration by interval equal to a *guard band*. These bands are needed to compensate for arbitrary delays incurred by transmitted packets due to signal propagation delays or clock drifts.
10. We assume that each mobile node has two buffers:
    - *MAC Buffer:* this buffer is required in order to store packets arriving during a time slot until the beginning of the next slot. When the buffer is full, packets are dropped and they are treated as lost packets.[1]
    - *ReTranmission Buffer:* this buffer stores transmitted packets, temporarily, until it receives a message from the next node. If it receives an *ACK* message, it drops the packet. On the other hand, if it receives an *NACK* message, it retransmits the packet after a random period of time.
11. We deploy the classical *shortest-path routing* protocol with a slight modification. The link costs are chosen to be the transmitted powers. Therefore, the objective is to route the packet from the source to the destination through the *minimum power path*.
12. The received power at any mobile node has to be greater than a minimum power level, denoted by *Min_Recv_Power*. This is crucial in order to guarantee reliable communication between the transmitter and the receiver. This value helps determine the power level at which a mobile has to transmit in order to directly reach a neighboring node.

[1] We assume the buffer length to be arbitrarily large (*infinite*). Accordingly, the probability of dropping a packet, due to buffer overflow, becomes arbitrarily small.

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13. Unidirectional links are expected to arise within this context, i.e. we might have a cluster of nodes that can communicate with each other but no packets can either enter or leave this cluster. Modifications to the protocol to eliminate this effect are being investigated.
14. The *Signaling Packet* format is shown in Figure 2 below,

Node ID	Neighbor ID	Transmit Power Level

Figure 2: Signaling Packet Format

where,
Node ID: identifier for the node broadcasting the signaling packet.
Neighbor ID: identifier for a direct neighbor to which the node is broadcasting the signaling packet.
Transmit Power Level: minimum power level needed to reach that neighbor.

15. The *Data Packet* format is shown in Figure 3.

Source ID	Destination ID	Current Node ID
Next Node ID	# Re-Transmissions	Payload

Figure 3: Data Packet Format

where,
Source ID: identifier of the node that generated the packet.
Destination ID: identifier of the packet's destination node.

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Current Node ID: identifier of the relay node at which the packet is currently stored on its path to the destination.
Next Node ID: identifier of the next relay node to which the packet is to be transmitted on its path to the destination.
Re-Transmissions: total number of retransmission attempts performed on that packet. (retransmission will be necessary whenever a packet encounters a collision)

16. The *Connectivity Table*, for the wireless ad hoc network shown in Figure 1, will have the format shown in Figure 4.

Node ID	Neighbor ID	Transmit Power Level
A	B	P_1
A	C	P_1
A	D	P_1
D	A	P_2
D	C	P_2
D	E	P_2

Figure 4: Connectivity Table Format

17. **Node Throughput** is defined as *percentage of successful transmission attempts.*
18. **End-to-End Network Throughput** is defined as *percentage of packets that reach their destinations successfully* and is denoted by η.
19. **Average Power Consumption** is defined as *average transmitted power/node* and is denoted by P_{av}.
20. The channel model includes only path loss and shadowing effects. We assume the *lognormal* random variable ξ to depict shadowing. Thus, the received power is given by,

$$P_R = (\xi/d^4) \cdot P_T$$

where,
P_T: power transmitted.
d: distance between the transmitter and the receiver.

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8-17-99
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Connectivity Range Optimization

Considering various conditions of connectivity and power control, it is straightforward to point out the following issues:

- Consider a wireless ad hoc network with *all mobile nodes using the maximum power level* (i.e. no power control). Accordingly, any mobile node can reach a large number of nodes in just one hop. The **advantage** of this approach is reaching a large number of nodes in a single hop and almost all of the nodes in the network in two hops. The **price paid** is however twofold, namely high power consumption and higher interference, which results in a larger number of collisions. If the link cost is taken to be the transmitted power, it is straightforward to notice that the cost of all the links are equal ($=P_{max}$). Hence *the minimum power routing* reduces to the *minimum hop routing*. This case serves as a reference case for comparison purposes.

- We next consider a wireless ad hoc network consisting of n nodes with a connectivity range of N, where $2 \leq N < n-1$. Each mobile node has a direct link to the closest N out of $(n-1)$ mobile nodes. We call these N nodes a *cluster*. Given N, the mobile node adjusts its power to reach at most the farthest node within its cluster. However, we assume that there is *no power adaptation within the cluster*. The **advantages** of this approach are lower power consumption and possibly lower interference than in the previous case. The **drawbacks** are the higher number of hops traversed in order to reach destination, and the possibility of having isolated clusters. It is worth mentioning that link costs (transmitted powers), in this context, are generally different depending on the radius of each cluster. Accordingly, the *minimum power routing protocol* is crucial to limit power consumption.
  Limitation: Since there is no power adaptation within a cluster, it is possible that a mobile node communicates with a node within its cluster using a power level higher than the minimum required power, and thereby possibly introducing more interference than that incurred in the case to be discussed next.

- Finally, we consider a wireless ad hoc network with connectivity N, where $2 \leq N < n-1$. Each mobile node has a direct link to the closest N out of $(n-1)$ mobile nodes. We assume, in this case, that there is *power adaptation within the cluster*. This approach reduces the powers consumed on various routes. Communication between nodes using the minimum power that guarantees reliable communication between the nodes minimizes interference. The advantages and drawbacks are the same as in the previous case. We would expect this approach to *outperform* (achieve higher throughput) the previous scheme at the expense of higher complexity. The *minimum power routing* is once again the candidate routing protocol.

- So far, N (connectivity range) is the only degree of freedom. This implies that the connectivity range is the same for all mobile nodes. The more general case is the one that assumes connectivity ranges to be generally different for different mobile nodes. Accordingly, there will be n degrees of freedom, i.e. $[N_1\ N_2\ \ldots..\ N_n]$ where N_j denotes the connectivity range of the *'j' th* node. The objective then is to search for the *optimal connectivity vector* among all possible connectivity vectors.

We consider the third case described above. Our objective is to solve the following minimization problem:

$$\min_{N} (-\eta + \alpha P_{av})$$

s.t.

$$P_{min} \leq P_{Ti} \leq P_{max}$$

Srikanth. V.K. Tamer ElBatt 8/19/99
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where,
P_{Ti}: transmitted power of node *i*.
α: fixed weighting factor that reflects the relative importance of the two components of the afore mentioned composite cost function.

The choice of the parameter α is rather arbitrary, and there is no well-defined procedure for choosing it. The following formulation is equivalent and much easier to implement,

$$\max_{N} \eta$$

$s.t.$

$$P_{av} \leq \beta$$
$$P_{min} \leq P_{Ti} \leq P_{max}$$

where β is the equivalent parameter and has a one-to-one correspondence to α.

Mobile Node Model

Each mobile node is modeled using the following three modules connected sequentially (shown in Figure 5).

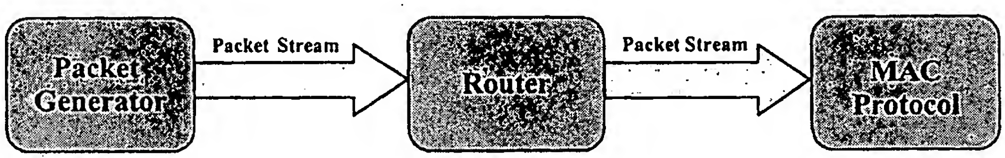

Figure 5: Mobile Node Model

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a. Packet Generator: This module generates data packets, with the *Data Packet* format explained earlier, according to some generic arrival process. Data packets are assumed to be of fixed size. Then, it sends each newly generated packet to the *Router* module which determines the next node on the packet's path to its destination.

b. Router: This module handles data packets of, possibly, three different types:

- New Packets: which are sent by the *Packet Generator* module.
- Forwarded Packets: which are received from neighboring nodes.
- Packets meant for retransmission: these packets are stored temporarily in a buffer and are retransmitted if they encounter a collision (indicated by a *NACK* message from the receiver). After a predetermined number of retransmission attempts, a packet is dropped from this queue.

The role of this module is to construct the connectivity and routing tables and to search for the minimum cost (power) route from a source to a destination [2]. It specifies the next node on this minimum power route, to which a given packet should be forwarded and it stores this information in the *Next Node ID* field of the packet. Finally, this module sends the data packet to the underlying *MAC* module which, in turn, is responsible for transmitting it to the next specified relay node.

c. MAC Protocol: This module receives a data packet from the *Router* module and transmits this packet to the next node. This is equivalent to broadcasting the packet. This module is also responsible for detecting collisions and requesting retransmissions for collided packets. To limit network overloading, the number of retransmission attempts for a particular packet are limited to some predetermined maximum, after which the packet is just dropped and is considered to be lost.

Protocol Description

The proposed protocol goes through the following three phases of operation (illustrated in Figure 6)[3].

1. Connectivity Specification Phase.
2. Connectivity Maintenance Phase.
3. Data Transfer Phase.

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[2] Link costs are taken to be the transmitted powers and hence the name *minimum power routing* follows.

[3] For convenience, we assume a TDMA system with slotted aloha multiple access protocol. However, any underlying contention based MAC protocol may be considered

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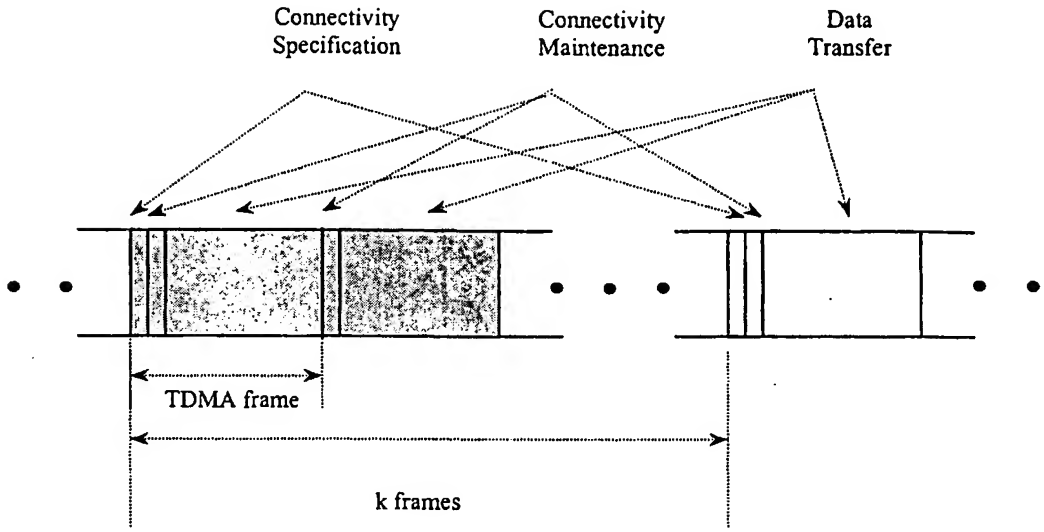

Figure 6: Protocol Operation Phases

In the following, we present a more detailed description for these three modes of operation.

Connectivity Specification Phase

In this section, we introduce two protocols that enable each node to dynamically adapt the connectivity range parameter N in order to achieve a near-optimal operating point. This is motivated by the fact that the optimal connectivity range changes with the dynamics of the configuration of the network characterized by the topology, nodes' mobility, and traffic load.

Periodic Update Protocol (PUP)

This protocol follows the following steps:

1. Initially, each node independently chooses the connectivity range to be the minimum i.e., the range N is set to *2*.
2. The node operates for a pre-specified number of frames (k)with this chosen value of N.
3. By the end of this period (called the *checkpoint*), the performance measure, namely the *end-to-end throughput* of this node is computed.
4. At this checkpoint, each node broadcasts its end-to-end throughput on the afore mentioned *reverse channel* [4]. This value is then stored in a data structure denoted by η_N.

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[4] This is essential for each node to compute the average end-to-end network throughput.

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5. The connectivity range is then increased by one, i.e. N is increased by one. The ad hoc system is expected to operate using this connectivity range for the next k frames.
6. At the next *checkpoint*, the new value of the *average end-to-end network throughput* is computed and stored in a data structure denoted η_N.
7. Compare η_{N-1} to η_N. One of the following two cases might arise:

If ($\eta_N > \eta_{N-1}$)
{
Increase the connectivity range to $N+1$ and go to step 6.
}
else {
Reduce the connectivity range to $N-1$ and go to step 6.
}

8. As long as the *average end-to-end network throughput* increases with N, we keep increasing N. This is done until the throughput starts decreasing with N, at some value of N, say at $N = i+1$. This implies that a maximum in the throughput is achieved at $N = i$, which is the connectivity range that achieves the maximum end-to-end network throughput for the current network configuration.
9. At each check point, compare the end-to-end network throughput with the throughputs achieved when $N=i+1$ and $N=i-1$. As long as $\eta_i > \eta_{i+1}$ and $\eta_i > \eta_{i-1}$, N need not be changed.
10. If the network configuration changes at some later time, such that this connectivity range $N = i$ does not achieve the maximum throughput anymore, then pick any of the two neighboring points, η_{i+1} or η_{i-1}, that achieves a higher throughput.
11. If $N = i+1$ achieves a higher throughput, then we further increase N in order to search for the new maximum. Go to step 6.
12. If $N = i-1$ achieves a higher throughput, then we further decrease N in order to search for the new maximum. Go to step 6.

Quasi-Periodic Update Protocol (QPUP)

This protocol is identical to the *Periodic Update* Protocol except that, when the network achieves maximum end-to-end throughput, the protocol less frequently attempts to test if the current throughput is still the maximum. The protocol takes advantage of the fact that the network under consideration consists of nodes of low mobility, i.e. the network topology changes slowly. Therefore, once the system reaches an operating point wherein the throughput is maximum, the protocol expects the throughput to stay at the maximum or a value very close to the maximum until the topology changes drastically. Thus, this protocol trades simplicity for performance. It is much simpler than the *Periodic Update* protocol, but there is a possible degradation in the end-to-end network throughput.

Connectivity Maintenance Phase

In this phase, each mobile node is responsible for keeping track of its closest neighbors (in terms of transmitted power) and updating its local connectivity tables accordingly. The time taken to update the network topology has to be small in comparison with the time elapsed between location updates. In the following descriptions, we present the functions performed by each mobile node during this phase of operation:

1. Each mobile node is assigned a *dedicated signaling time slot of a global signaling channel.* (This slot might be assigned in a round robin fashion). In this slot, the node broadcasts a beacon packet, using the P_{max} power level, to all other nodes in the area of interest. Note that, the MAC protocol employed for signaling slot assignment is contention-free, and hence no collisions occur in this phase.

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2. In slot i, all other nodes obtain this beacon signal of node i. Accordingly, they record the received power level and store it in a data structure along with the transmitting mobile node's ID. This functionality is simulated in our model using the *Power Measurement* procedure described later in this section. Note that *average power measurements* are used, rather than *instantaneous power measurements*. This is motivated by the fact that average power smooth out variations due to fast multipath fading which is not compensated for with this scheme.
3. By the end of this phase, mobile node i, $1 \le i \le n$, is expected to have a ranking of all other nodes, and this ranking is based on the received power levels from the other nodes. Based on this ranking, node i picks its N closest nodes (having highest average received power levels at this node's site) as his *direct neighbors*. Subsequently, node i updates its local connectivity table to add the mobile node IDs of its direct neighbors.
4. Each node then *adapts* its transmitted power level in order to achieve the required connectivity, i.e. direct links are established to *only* to the N closest nodes.
5. Node i updates its local connectivity table in order to store the link costs to the direct neighbors. The link cost in this protocol is taken to be the transmit power level.
6. Finally, each node broadcasts a *Signaling Packet* containing its local connectivity table information in the signaling channel. By the end of this phase, the global network topology is completely defined and each mobile node is expected to have this information in its local routing table. This information is essential for the table driven routing protocols executed at each node site.

Power Measurement

This procedure simulates the operation of mobile node j capturing the beacon signal transmitted by node i during node i's allocated signaling slot, where $1 \le i,j \le n$ and $i \ne j$. The received signal strength depends solely on the transmitted power level (which is assumed to be P_{max} during this phase), the current positions of nodes i and j, and the effect of the log-normal shadowing. Thus, the received power level is computed using the following formula:

$$P_{R\,ji} = (\xi/d_{ji}^{4}) \cdot P_{T\,i}$$

where,
$P_{R\,ji}$ = received power level at node j from node i.
$P_{T\,i}$ = transmitted power by node i.
d_{ji} = current distance between node j and node i.
ξ = lognormal shadowing coefficient.

As pointed out earlier, we rely on *average power measurements* rather than *instantaneous power measurements*. This is due to the fact that instantaneous measurements could be inaccurate in reflecting the slowly varying channel conditions, due to fast multipath fading impairments. Therefore, a moving average is computed by each node to average out the fast fading over a pre-specified number of most recent instantaneous power measurements. Note that the moving average window length should be chosen carefully depending on the fast fading characteristics and the mobility patterns of the nodes.

Power Control

There are two suggested approaches for power management in mobile ad hoc networks, i.e.,
(a) *to have no power control within the cluster*[5] and

[5] A cluster consists of the node and its direct neighbors as defined earlier.

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(b) *to have power control within the cluster.*

The basic difference between the two schemes is that in the former the power needed to communicate with the farthest node in the cluster is also used to communicate with any closer node in the cluster. On the other hand, the latter scheme suggests communicating with each node *with the minimum power* it needs for reliable communication with that node. This is expected to introduce less interference as compared to the former scheme to other simultaneously occuring transmissions of other nodes. In either case, the objective of thus defining a cluster is to reduce collisions/interference and thereby improve the end-toend network throughput. Furthermore, this approach reduces the average system power consumption, since the nodes are not transmitting using P_{max} all the time, they might use much lower power levels depending on their distance from their direct neighbors.

As mentioned earlier, we assume a minimum required level of received power, denoted *Min_Recv_Power,* that is necessary to guarantee a certain maximum acceptable bit error rate *(BER).* The minimum power level to be transmitted by node *i* such that at least the *Min_Recv_Power* level is achieved at node *j*, for a given configuration, is given by:

$$P_{T\,ij} = P_{max} \cdot (Min\_Recv\_Power/P_{Rji})$$

where,
$P_{T\,ij}$ = power transmitted by node *i* such that the transmission range does not exceed beyond the distance to node *j* , and
$P_{R\,ji}$ = power received by node *j* when node *i* transmits at P_{max}.

Exchange Information

For medium size ad hoc networks, each mobile node is expected to have a copy of the global network topology. So far, each node has constructed its own local connectivity table that contains neighboring node IDs and the link costs (transmitted power levels) to reach these neighbors. Each node, in order to exchange its connectivity information with other nodes, broadcasts its connectivity table to its neighborhood nodes in a dedicated slot. After an initial transient phase, all nodes have the global network topology.

For large networks, it is infeasible for each node to obtain or store the global topological information due to the heavy communication overhead incurred and also due to memory constraints. Accordingly, this scheme supports small to mid size wireless ad hoc networks or subnetworks of a large wireless ad hoc network.

Data Transfer Phase

At the beginning of this phase, the network topology is completely defined, and the mobile nodes are ready to relay information from any source to any destination. There are two main functions performed by each mobile node in this phase, which are

(i) deciding the next node to which a given packet is to be forwarded on its way to its destination, and
(ii) transmitting the packet over the shared radio link using the underlying MAC protocol. In the following, we introduce a more detailed description of these functions.

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Traffic

In this system, we consider only IP like connection-less data traffic. Thus, there is no upper bound on delays or jitter. The only QoS we consider are the *Packet Loss Rate* (*PLR*), and the *node and network throughputs*. Packets streams, generated by each mobile node, follow a generic arrival process. The average packet inter-arrivals per *slot duration* determines the network loading.

Minimum Power Routing

The *Minimum Power Routing* (MPR) protocol proposed is a *hop-by-hop shortest path routing* mechanism and the link costs are the transmitted power levels. The *Router* module in the mobile node is responsible for performing the routing task.

. The routing protocol goes through the following steps:

1. Based on the routing table constructed in the *Connectivity Maintenance* phase, it creates the set of all possible routes from the source to destination.
2. The routing protocol employed falls within the general class of *shortest path routing*. It searches, within the created route set, for the minimum cost route from source to destination.
3. Determine the next relay node on the minimum power route.
4. Modify the *Next Node ID* field in the data packet being routed.
5. Copy the packet to the retransmission buffer until its successful reception at the next node is indicated via an *ACK* message.
6. Send the data packet to the *MAC* module in order to be forwarded to the next relay node in the path.

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